Image Current Heating in Cold-Bore Superconducting IDs

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Absract

The NSLS is vigorously pursuing the design of NSLS-II – a new ultra-low emittance 3 GeV 3rd generation storage ring with a top-off injector to eventually replace the existing facility [1]. To achieve the 1000-fold increase in undulator brightness NSLS-II will rely heavily on superconducting MGUs. The present MGU design includes 5 mm full gap inner chamber cooled to liquid He temperature. The amount of heat deposited by the beam image current into this chamber is very important to estimate the feasibility of the cryogenic design.

For the few mm bunch-length of interest, the copper is going to be in the extreme anomalous skin effect regime, and therefore the usual resistive wall impedance formulas do not apply. It is possible, however, to calculate the heat deposition (as well as other impedance-related quantities) based on the well-known expressions for surface resistance in the extreme anomalous skin effect regime [2], at least when the bunch length is not too short. In this talk I will give the heat load estimates for the NSLS-II. I will also discuss the applicability limits of the present treatment as well as possible "correction factors" due to transition effects at the ends of the device, surface roughness, magneto-resistance, etc. Finally, I will present some calculations applicable to linac-based machines with very short bunches where the image current generated heat (for CW linacs) and/or energy spread could be of interest as well.

[1] NSLS UPGRADE CONCEPT
B. Podobedov, J. Ablett, L. Berman, R. Biscardi, G.L. Carr, B. Casey, S. Dierker,
A. Doyuran, R. Heese, S. Hulbert, E. Johnson, C.C. Kao, S.L. Kramer, H. Loos,
J.B. Murphy, R. Pindak, S. Pjerov, J.Rose, T.Shaftan, B. Sheehy, P. Siddons, N. Towne,
J.M. Wang, X.J. Wang, L.H. Yu,
Proceedings PAC03, 2003

[2] Landau & Lifshits, Physical Kinetics. The original derivation was given by
Reuter and Sondheimer, Proc Roy. Soc. (London) A195, 336, 1948.

Outline

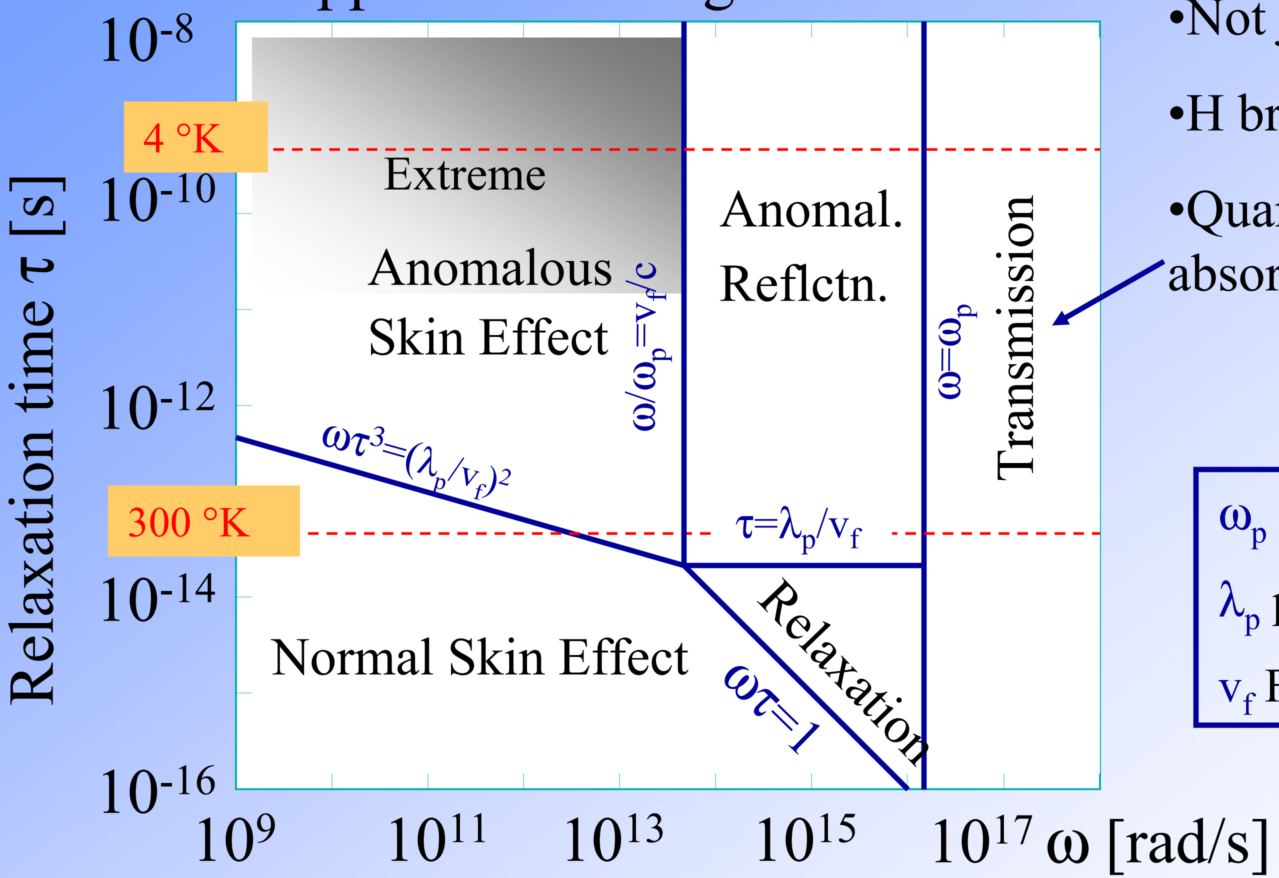
- Motivation
- Skin Effect Regimes
- Basic Image Current Heat Load Estimates for NSLS-II
- Possible Correction Factors
- Effects in Linacs
- Concluding Remarks

Motivation

- Image current heat generated in small-gap super-conducting undulators could significantly affect the feasibility of cryogenic design for NSLS-II and other machines
- Accurate estimates and/or measurements of this effect are needed

Skin Effect Regimes

Approximate diagram for Cu



- Not just 2 regimes
- H brings up more…
- Quantum effects add absorption bands here

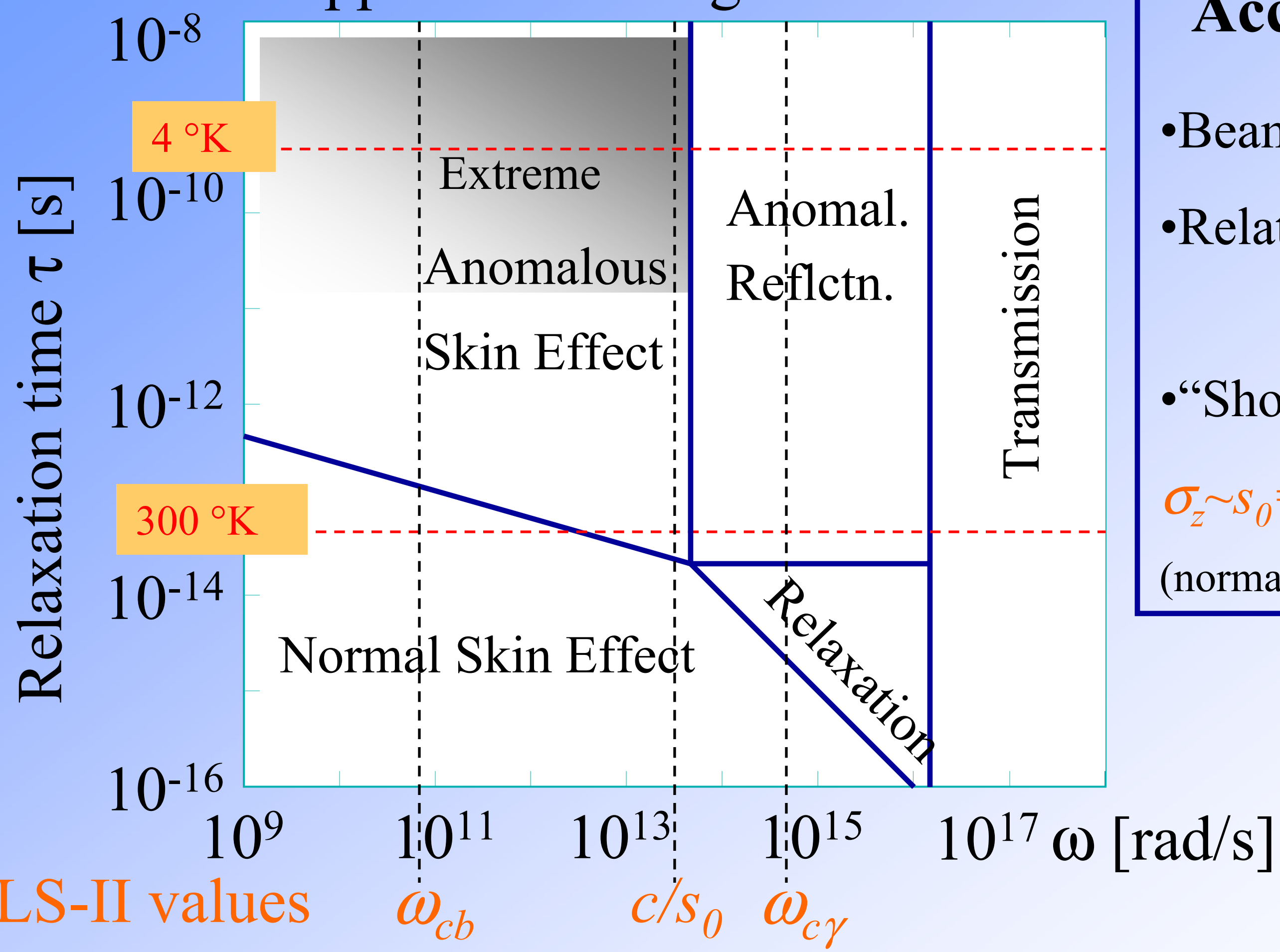
ω_p plasma frequency

λ_p plasma wavelength

v_f Fermi velocity

Skin Effect Regimes for MGUs

Approximate diagram for Cu



Accelerator Beams

- Beam cut-off $\omega_{cb} \sim c/\sigma_z$
- Relativistic cut-off

  $\omega_{c\gamma} \sim \gamma c/a$
- "Short bunch regime" for

  $\sigma_z \sim s_0 = (2a^2/\sigma_{cond} Z_0)^{1/3}$

  (normal skin effect x-pression)

σ_z – rms bunch length

a – beam pipe radius

σ_{cond} – conductivity

Z_0 – free space impedance

Surface Resistance for Normal and Anomalous Regimes

- Normal skin effect:

$$Z_{s\_normal}[\omega] = \sqrt{\frac{\omega\,\mu}{2\,\sigma_{cond}}}\,(1 - i)$$

- Extreme Anomalous Skin Effect (ASE):

$$\alpha = 3(l/\sigma_{cond})^2 Z_0 \omega/(4c\rho^3) >> 1$$

l – mean free path, ρ - DC resistivity

$$Z_{s\_extreme}[\omega] = \left(\sqrt{3}\,\pi\left(\frac{Z_0}{4\,\pi\,c}\right)^2\right)^{1/3}\left(\frac{l}{\sigma_{cond}}\right)^{1/3}\omega^{2/3}\left(1 - i\sqrt{3}\right)$$

specular reflection case

- Empirical formulas exist for (“non-extreme”) ASE

Factors $\sim\alpha^{-0.28}$, less agreement with experiments due to surface, *H*, etc.

- Calculate heat

$$P/L = \frac{1}{2\pi a}\int \mathrm{Re}[Z_s(\omega)]\left|\tilde{I}_{beam}(\omega)\right|^2 \frac{d\omega}{2\pi}$$

centered through round pipe

Image Current Heating of IDs at Room Temperature

- Long bunch "Piwinski" regime (σ_z>>s_0)
- Beam loses energy into skin layer
- Equal losses when Gaussian beam is
  1. Centered in a pipe of radius *a*
  2. Half-way between infinite plates spaced by 2 *a*
  3. Distance *a* above single infinite plane
  4. Centered in elliptical pipe with axis 0.93 a x 1.4 a (minimal loss for given height)

I – total average current	0.5A
σ_z – rms bunch length	3.9mm ($c*13$ps)
d – bunch spacing	$c/(500\text{MHz})$
a – half beam gap	2.5mm
σ_{cond} – conductivity	$5.8\times10^7\,(\Omega\text{m})^{-1}$
Δ – max. off – center error	0.5mm
L – undulator length	2m
Z_0	377 Ω

NSLS-II

$$\frac{P}{L}[W/m] \approx 0.02\,\frac{I^2 d}{\sigma_z^{3/2} a}\sqrt{\frac{Z_0}{\sigma_{cond}}}$$

$$\Rightarrow \quad P_{total} = 52\,\text{W}$$

Conservative Estimate:

- Ignore bunch lengthening
- Ignore chamber ellipticity
- Allow for Δ by *a* -> *a* - Δ
- 2/3 RF buckets filled ->power boosted by 50%

Harmonic RF may reduce this a factor of 5 (σ_τ->40 ps)

Image Current Heating of IDs at 4.2 K

- At low T Normal Skin Effect breaks down
- Cu at 4.2 K is well into the Extreme Anomalous Skin Effect Regime, $\alpha \sim 2\ 10^6$
- Use $Z_{s\_extreme}$ for surface impedance
- Piwinski formula gets modified to

$$l - e^- \; mean\ free\ path$$

$$\frac{\sigma_{cond}}{l} = 1.54 \times 10^{15}\, m^{-2}\Omega^{-1}$$

Same parameters and conservative estimate assumptions as for room temperature case

$$P/_L\,[W/m] \approx 0.009\, \frac{I^2 d}{\sigma_z^{5/3} a}\, Z_0^{2/3} \left(\frac{l}{\sigma_{cond}}\right)^{1/3}$$

$$\Rightarrow \quad P_{total} = 10\mathrm{W}$$

Exceeds off-the-shelf cryo-cooler capacities !

Harmonic RF may reduce this a factor of 6 (σ_τ->40 ps)

Surface Impedance Correction Factors

- Magneto-resistance (MR)

When H||E MR is small, AC MR is very small, $Z_{s\_extreme}$ independent of $H_{\perp}$

Confirmed experimentally for Cu @ GHz frequencies and *LHe* temperature

H=0 - 5.8 T -> few % resistance change [J.T. Rogers, Appl. Phys. Lett, 52, 26, 1988]

Yet LHC measurements (Cu @ 20 K, f<2 GHz for σ_z=7.5 cm) cite H among causes for disagreement [F. Caspers, LHC-Proj-Rep 307, 1999]

- Surface and bulk waves

Plenty of papers, mostly theory, typically small corrections

- Cyclotron resonance

Not applicable to MGU geometry

- Surface-roughness

Still should be looked at, esp. for short bunches

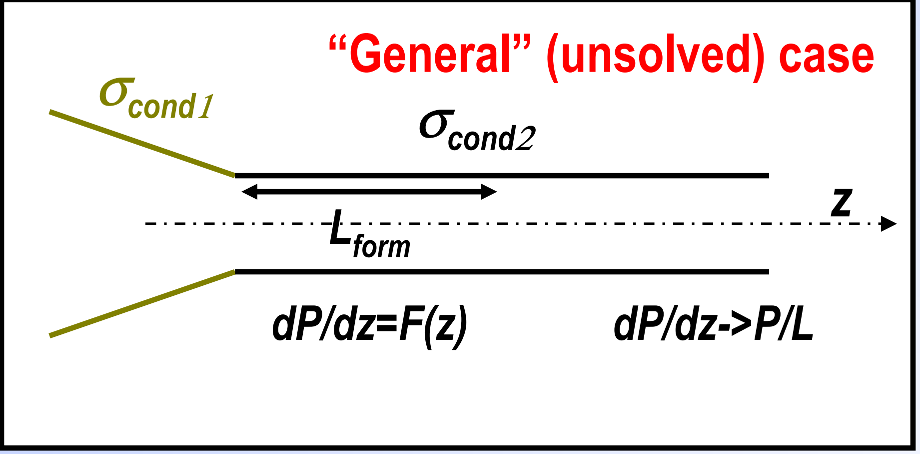
- Finite length (transition effects)

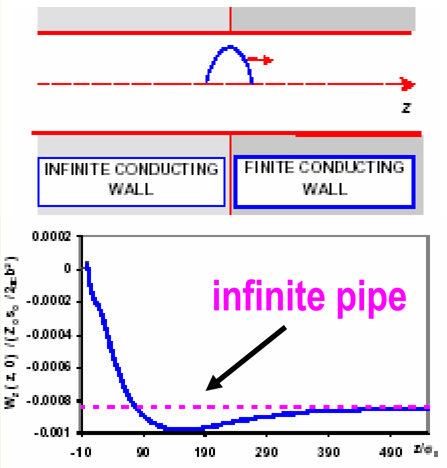
Transition Effects and Heat

- Considered so far is infinitely long pipe with constant *a* and σ -> no *z* dependence for $Z(\omega)$, heat, etc.
- Generally not applicable near transitions due to

1. Formation length L_{form} for resistive wall impedance is finite
2. EM waves resulting from geometric wake (X-section change) interact with resistive pipe causing more heat
(this is NOT image current heat, appears to be small, to be published B. Podobedov & J.M. Wang, 2003)

- More progress needed …





M. Ivanyan, EPAC-02

- Normal skin effect
- Limited applicability
- L_{form} could be large
- *Max(dP/dz) > P/L*

Effects in Linacs

General

- Bunches are short -> high I_{peak}
- There is always image current induced energy spread δE, scaling is the same as for heat: $\delta E_{cold}/\delta E_{warm} = const*P_{cold}/P_{warm}$
- Linac beams are not Gaussian, P and δE come out higher
  Example: multiply P_{warm} by 2.3 for rectangular bunch same FWHM
- Yet to derive formulas for ultra-short bunches $\sigma_z \sim s_0$ (think <~10μm)

Heat in MGUs

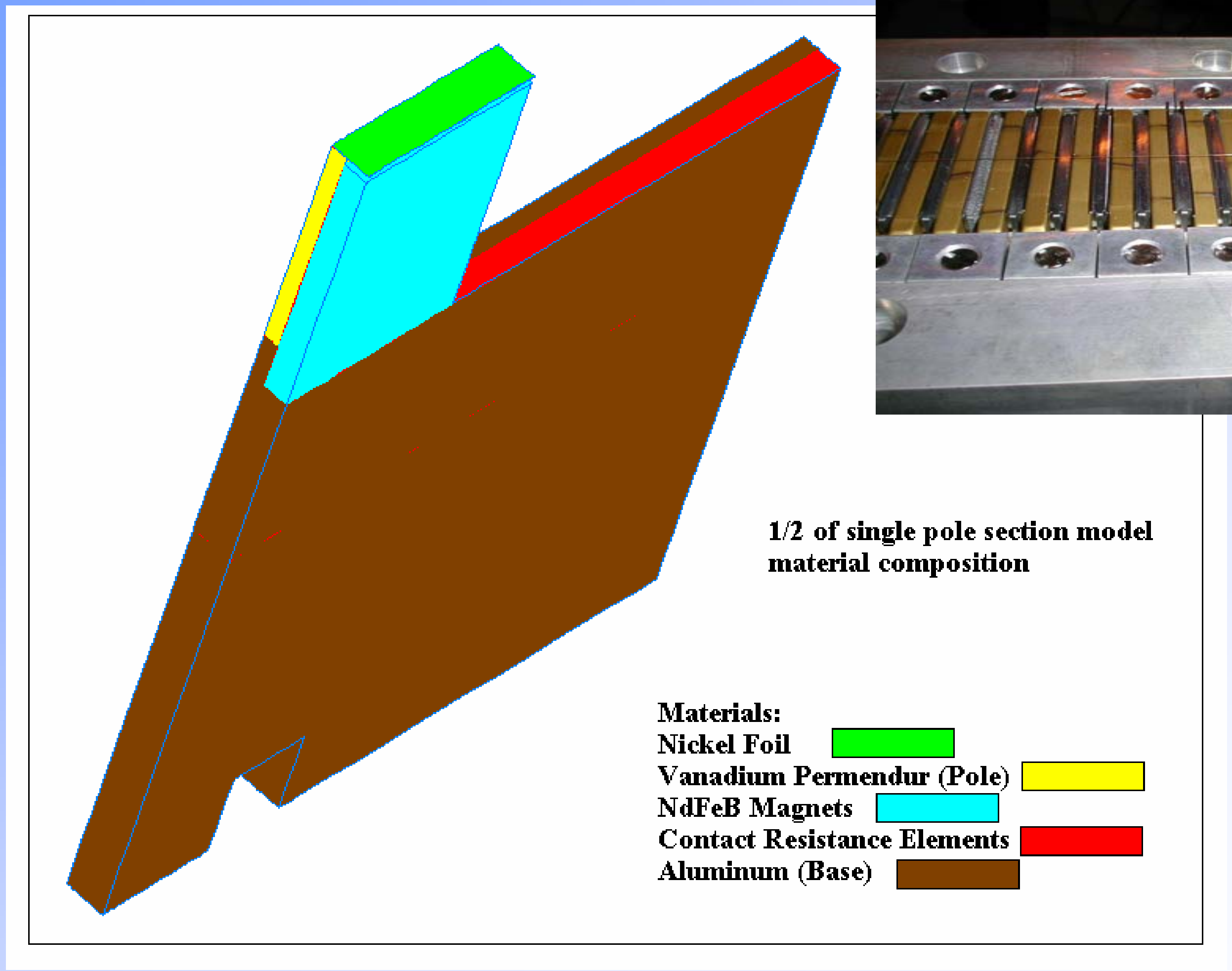
- Low rep-rate/low average current linacs – no heat
- High average current (CW) linacs - heat could be large
- Example: JLab 10 kW IR FEL upgrade [parameters (thanks S. Benson) I=60 mA, 60pC/bunch@750 MHz, stainless steel pipe 13mm diameter. I assumed 200 fs rms Gaussian (!) bunch]

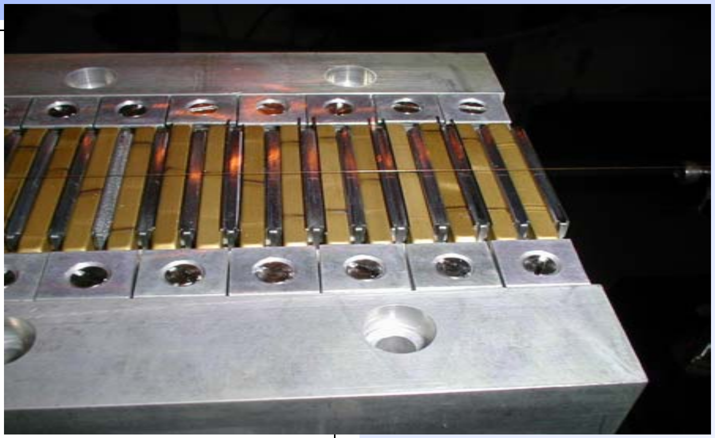
Page 8 formula gives P/L=156 W/m

P/L is 27 W/m if they would use warm Cu, 10 W/m for cryo

(not that they need to, this is for illustration only)

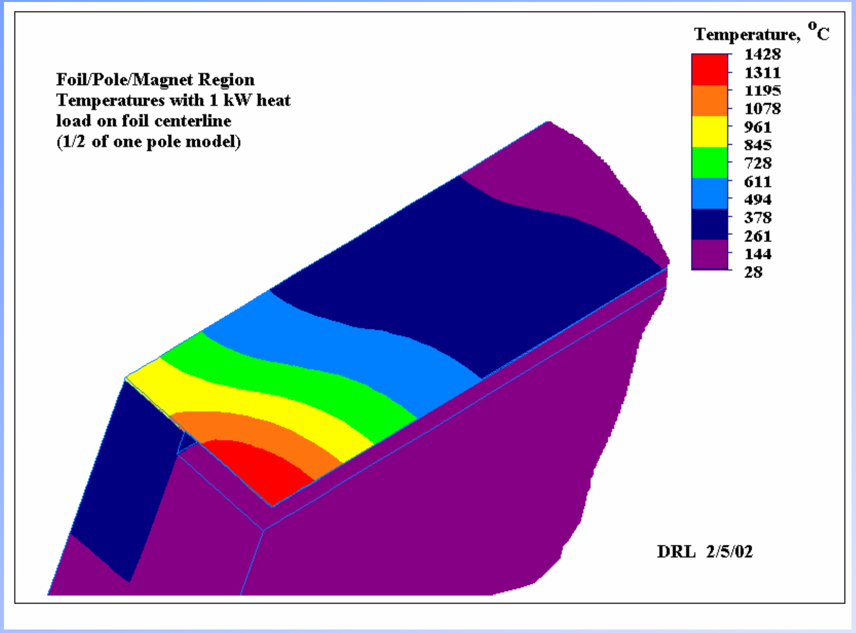
NSLS MGU Magnet Section Materials

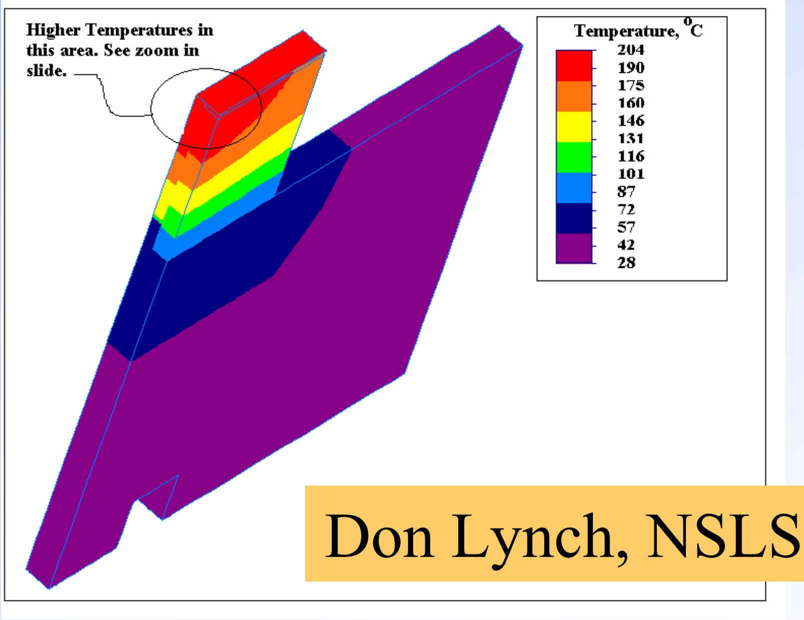




200 mA 100 fs bunches in NSLS X-ray ring ?
X13 PM MGU Thermal Analyses

Heat flux of 3 kW/m assumes Cu-plated Ni foil, Gaussian beam with σ_z=30 μm, 0.5 mm off center (a=1 mm), rep rate of 1.3 GHz and I_{av}=200 mA, normal skin effect





Don Lynch, NSLS

Foil melts

Permanent demagnetization

½ period of MGU, sliced at centerline, with 1 kW total power on foil. On left is zoom in on foil at centerline (note max. temperature on foil adjacent to gap between foil and magnet) Temperatures are in deg C. DRL 2/5/02

Concluding Remarks

- Image currents may create a lot of heat
- Simple estimates are done for Cu @ 4.2K (assuming extreme anomalous skin effect)
- There are lingering "correction factors", most appear small, yet measurements (for real ID chamber, H, and ω) could add confidence
- We estimate the total heat load for the NSLS-II ring <10 W (Cu @ 4.2K) *Marginally feasible?*
- Image current heat may prohibit MGUs in high current CW linacs (cold SC and even warm-bore PM MGUs)
- There are other sources of heat (radiation, electron clowd, geometric wake, etc.)